Measurement of Turbulence with Acoustic Doppler Current Profilers -- Sources of Error and Laboratory Results

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Abstract

Acoustic Doppler current profilers (ADCPs) provide a promising method for measuring surface-water turbulence because they can provide data from a large spatial range in a relatively short time with relative ease. Some potential sources of errors in turbulence measurements made with ADCPs include inaccuracy of Doppler-shift measurements, poor temporal and spatial measurement resolution, and inaccuracy of multi-dimensional velocities resolved from one-dimensional velocities measured at separate locations. Results from laboratory measurements of mean velocity and turbulence statistics made with two pulse-coherent ADCPs in 0.87 meters of water are used to illustrate several of inherent sources of error in ADCP turbulence measurements. Results show that processing algorithms and beam configurations have important effects on turbulence measurements. ADCPs can provide reasonable estimates of many turbulence parameters; however, the accuracy of turbulence measurements made with commercially available ADCPs is often poor in comparison to standard measurement techniques.

Introduction

Acoustic Doppler current profilers (ADCPs) have been available since the mid 1970's (Gordon, 1996) and are typically used to measure mean velocities, long-term velocity trends and river or estuary discharge. Recent models also show potential for measuring turbulence. However, several factors pertaining to the physical configuration of ADCPs and the accuracy with which they measure Doppler shifts may limit the accuracy of turbulence statistics computed from measurements collected with commercially available profilers. This paper discusses some of these potential sources of error, how their effects can be minimized, and how future advances in technology might overcome them. A general knowledge of ADCP terminology and operation on the part of the reader is assumed; background on these subjects is given by Gordon (1996).

Laboratory measurements were made with two pulse-to-pulse coherent ADCPs: a Nortek[4] High Resolution ADCP (HR-ADCP) and an RD Instruments (RDI) Workhorse Rio Grande ADCP (RG-ADCP). Measurements were made in 0.87 m of water in a 1.8-m wide flume. ADCP measurements are compared to acoustic Doppler velocimeter (ADV) measurements to illustrate the effects of the factors relating to the physical configuration of the ADCPs and the accuracy with which they measure Doppler shifts. This study was done in cooperation with the Ven Te Chow Hydrosystems Laboratory at the University of Illinois at

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Turbulence is a random or quasi-random process characterized by velocity fluctuations; it occurs in most surface-water flows and affects several processes, including energy dissipation, sediment and contaminant transport, mixing, and scour (Tennekes and Lumley, 1972). Because of its random nature, turbulence typically is quantified through statistics, which are often based on velocity fluctuation time series. Instruments commonly used to measure turbulence include microscale profilers, hot-wire and hot-film anemometers, particle-image velocimeters (PIVs) and laser Doppler velocimeters (LDVs). Statistical descriptors of turbulence include mean velocity, turbulence intensities (standard deviation), turbulent kinetic energy (TKE), Reynolds stresses (a tensor formed from velocity fluctuation cross-correlations), spectra, integral time scale, eddy viscosity and mixing length.

The methods typically used to measure turbulence can be time- and/or labor-intensive and may require frequent instrument calibration and maintenance, intensive post-processing of data, or an extremely high level of user interaction; however, some methods measure only at a point or over a small area. The use of ADCPs as an alternative method is advantageous for several reasons.

1. ADCPs can measure a profile of semicontinuous "points" simultaneously and, therefore, can potentially increase the spatial distribution of the data. Instead of measuring a few selected points individually, ADCPs can simultaneously measure most of the water column.
2. ADCPs, as non-mechanical instruments, make nonintrusive measurements, and thereby virtually eliminate the possibility of flow disturbance over most of the profile.
3. Most commercially available ADCPs measure three-dimensional velocities by using multiple beams, but there is a critical assumption required.
4. ADCPs do not require frequent calibration; the only form of calibration required is periodic operation checks (Lipscomb, 1995).
5. Once the operating principles and procedures of the instrument are understood, ADCPs are relatively easy to use in the field and are often used for unattended long-term monitoring, for example Gartner and Cheng (1996).

These capabilities allow ADCPs to greatly increase the spatial distribution of turbulence measurements, or even to make turbulence measurements feasible where previously they were not.

Sources of Error in ADCP Turbulence Measurement

The use of commercially available profilers to measure turbulence has several advantages over other methods but requires consideration of two main sources of error--limitations of signal generation and processing algorithms, and the physical configuration of the instrument transducers. Signal generation and processing algorithm considerations include Doppler-shift measurement errors and limited temporal and spatial resolution. The physical configuration of the transducers causes errors in resolved multi-dimensional velocities measured in inhomogeneous flow and difficulty in near-boundary sections of profiles as a result of reflection of side-lobe energy.

Doppler-shift measurement errors are essentially errors in measuring radial-beam velocity and take two forms--random inaccuracies in measurement of Doppler-shift, and nonrandom errors caused by limitations of the measurement technique. Both forms of errors can have important consequences in turbulence measurements, and both are strongly dependent on the specific processing algorithms used by an instrument.

Random Doppler-shift measurement errors, which collectively form Doppler noise, are errors in a single part of a profile in a single beam. These errors are analogous to the uncertainties associated with any scientific measurement, but the magnitude of this uncertainty can be large compared to the velocity being measured. The average magnitude of random Doppler-shift measurement errors is strongly dependent on the type of pulse generation and processing used by the instrument; for example, incoherent or pulse-to-pulse coherent. Several manufacturers have designed special high-resolution, low-noise modes or instruments such as pulse-to-pulse coherent modes, but the increased accuracy is often achieved at the cost of reduced profiling range and/or robustness in high-velocity or high-turbulence conditions.

Nonrandom errors in Doppler-shift measurement are often the result of limitations of processing algorithms. For example, ambiguity errors can occur in phase shift measurements; that is, if the velocity exceeds the expected velocity range a corresponding phase shift outside of the expected –180° to 180° range occurs. A 360° error results because the instrument cannot distinguish between a 190° and a -170° phase shift. Other nonrandom errors are instrument- and mode-specific; these may include loss of data because of shear, or recurring spikes in the velocity time series. These errors may be specific to a single bin, or they may affect the entire profile. Errors in Doppler-shift measurement can also depend on the flow being measured; that is, the flow itself can affect the form of the reflected pulse, sometimes making the Doppler-shift difficult to resolve (Sontek, 1996).

Quantification of turbulence statistics using velocity fluctuations requires an accurate velocity time series that is measured at temporal and spatial scales appropriate to the flow (Hinze, 1975). Ideally, a turbulence measurement resolves the smallest temporal and spatial scales of the flow. Full description of velocity fluctuations requires that the temporal measurement rate be greater than the Nyquist frequency of the flow, or twice the frequency of the smallest eddies (Bendat and Piersol, 1986). The spatial measurement volume must be smaller than the volume of the smallest eddies, which can be described by the Kolmogoroff microscale (Tennekes and Lumley, 1972). In a river that was 5 m deep and had an average velocity of 1 m/s, Nezu and Nakagawa (1993) scaled the smallest eddies with frequency of 3 Hz and length scale of 0.6 mm. The maximum frequency increases with velocity and decreases with depth, and the minimum length scale decreases with velocity and increases with depth.

The fastest pinging commercially available profiler measures at 20 Hz in a special mode; in contrast, most profilers measure at 5 Hz or less, and many measure at less than 1 Hz. Bottom boundary layer measurements made by Cheng and others (2000) in an estuary at about 1 Hz, the maximum rate of the instrument used, did not resolve the small scales of the flow. Measurement rate depends on the number of bins included in the profile; that is, as more bins are added, the measurement rate gets slower.

Some instruments have a factory-configured number of pings that are included in each ensemble. For example, point-measuring ADVs typically ping at about 250 Hz, but their maximum recording rate is 25 Hz, and the Nortek HR-ADCP averages about 20 pings per ensemble with a maximum recording rate of approximately 0.5 Hz. Averaging pings not only results in slow measurement rates but also can bias velocity fluctuations towards the mean. Slow single-ping sampling can measure the full range of velocities, if given enough sampling time and if the measurement time scale is uncorrelated with the flow time scale.

The spatial resolution of each radial velocity measurement in a bin is defined by the angular width of the beam, the diameter of the acoustic transducer, and the bin size. The angular width of ADCP beams typically is small--about 1° (a 1.7-cm increase over a range of 100 cm).

Transducer diameters in high-frequency (around 1.5 MHz) ADCPs can be as small as 2 cm, but 5- to 10-cm transducers are more common. Low-frequency (75 KHz or lower) ADCPs and older (RDI Broadband and Narrowband) ADCPs have even larger transducers. Bin sizes have an even larger range, from a minimum of 1.6 cm for a high-resolution pulse-to-pulse coherent ADCP to a maximum of several meters. Corresponding measurement volumes can range from 5 cubic centimeters to hundreds of thousands of cubic centimeters for low-frequency Broadband systems. The smallest bin and transducer combination is then 23,000 times larger than the smallest expected eddy volumes in a river.

Although currently available ADCPs cannot resolve the smallest structures in the flow, many turbulence statistics, such as turbulence intensities, are determined primarily by the large-scale structures. A good estimate of these statistics can often be obtained from measurements at large scales. Low-frequency phenomena, such as tides, can be measured easily; for example, Lohrmann and others (1990) show measurement spectra with a clear tidal peak. Infrequent sampling or sample averaging, however, will severely limit or preclude calculation of statistics such as high frequency spectra, autocorrelations, and integral time scale.

ADCPs use multiple beams and operate on the assumption that in a given bin the velocity is equal in each of the beams to resolve multi-dimensional velocities from one-dimensional beam velocities. This assumption is not important for point instruments that use *bistatic* transducers and a co-located measuring volume, such as ADVs (similar to that shown in Figure 1a). Commercially available ADCPs, however, use *monostatic* diverging beams; they transmit pulses and receive echoes with the same transducers (Figure 1b) and, therefore, they measure in multiple locations. The distance between the measurement volumes varies with beam angle and configuration but typically scales with the distance of the measurement volume from the instrument. The distance between beams is large in relation to the size of the small-scale turbulence in the flow and is comparable to the size of large-scale turbulence; thus, the velocity is not necessarily equal in adjacent beams.

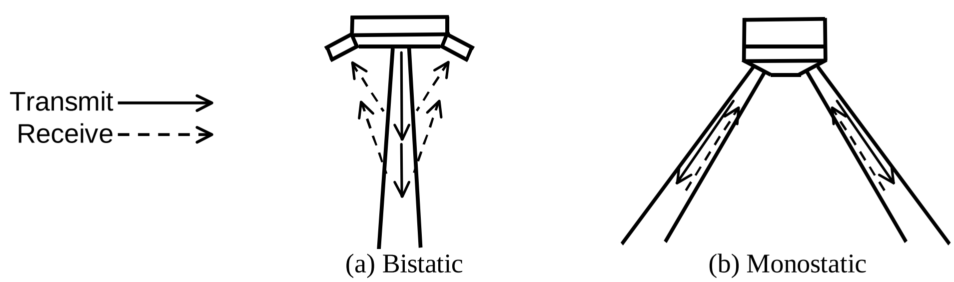


Figure 1. Schematic diagram of two-dimensional bistatic and monostatic profilers

If the velocity in each of the beams of a bin is not equal to the velocity in the other beams, errors are introduced into resolved velocities. For example, consider a two-beam monostatic ADCP that has one beam in upward flow and one beam in downward flow, with no horizontal flow in either beam (Figure 2a). This produces the same radial-beam velocities as a homogeneous horizontal velocity (Figure 2b), which is how the instrument interprets it. Increasing the distance from the instrument and thereby increasing the beam spread also increases the magnitude of this error; Gargett (1994) illustrated this by comparing a resolved vertical velocity with a directly measured vertical velocity. The use of a vertical beam to directly measure vertical velocity partly avoids the problem of inhomogeneous flow.

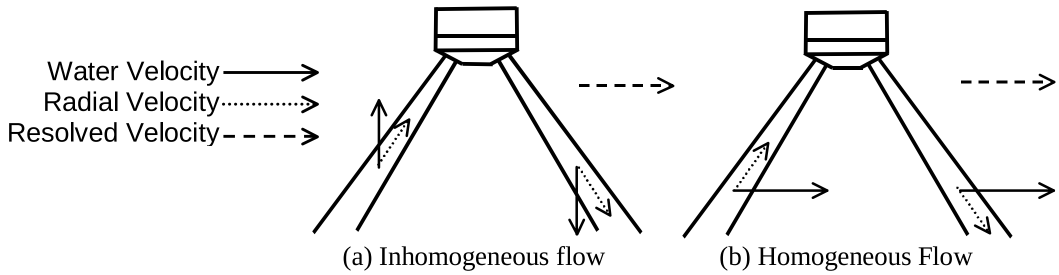


Figure 2. Resolution of multidimensional velocities and inhomogeneous flow

Two other sources of error in measurement of turbulence with ADCPs are side-lobe interference and transducer ringing, both of which render unusable data for a part of the water column profiled by the ADCP. Side-lobe interference affects a part of the profile near the far boundary, either the bottom or surface, depending on instrument orientation. Transducer ringing affects the part of the profile adjacent to the instrument. Comparison of the spatial distribution of ADCP data with point measurements may indicate that the acoustic contamination of these areas is insignificant. The areas affected, however, are often of interest in studies dealing with turbulence.

Laboratory Results

The several sources of error inherent in using currently available commercially available ADCPs to measure turbulence have a wide range of effects on computed turbulence statistics. The contribution of each factor can vary, depending on the physical configuration of the ADCP, the processing algorithms, and the flow being measured. Examples of these effects on a few turbulence statistics are described below. These results were obtained in laboratory measurements made with two pulse-to-pulse coherent ADCPs--a 600-kHz RD Instruments Workhorse RG-ADCP, and a 1.5-MHz Nortek HR-ADCP. Resulting profiles were then compared to measurements made with an ADV.

A one-dimensional time series measured in the beam of the RG-ADCP with an ADV (Figure 3) shows that the ADCP captured the general velocity trend at time scales larger than about 2 seconds, but produced large departures from the actual velocity measured with the ADV. These departures are a result of Doppler noise and the low temporal and spatial resolution. Doppler noise is presumably the primary cause of errors. The loss of fine details of the flow that were captured by the ADV is mainly due to the slow measurement rate (about 5 Hz). The combination of the slow measurement rate and Doppler noise appears to overwhelm measurement volume errors (5-cm bins; 320-cm^3 volume). The overall error in the one-dimensional radial (the component in the direction of the beam) turbulence intensity is 44%.

Resolving the same time series along the streamwise direction by using one additional beam (Figure 4) causes the ADCP time series to become much “noisier”, and makes even the larger flow structures difficult to discern. The error in streamwise turbulence intensity is 94%, more than twice that of the radial turbulence intensity. This time series was measured 66 cm from the instrument in 0.87 m of water.

The two main factors that cause differences between radial and resolved streamwise turbulence intensities are the angle of the acoustic beam relative to the streamwise direction and inhomogeneity of the flow between beams. The first of these affects both ADCPs and ADVs and is caused by the angle of the acoustic beams. Only the component of the velocity parallel to the acoustic beam is actually measured; therefore, a unit horizontal velocity equals less than a unit radial-beam velocity in a non-horizontal acoustic beam. The conversion from radial-beam back to horizontal velocity then magnifies the radial-beam velocity, including any noise. The second effect occurs only in the ADCP and is a result of instantaneous inhomogeneity of the flow and measurement at multiple points.

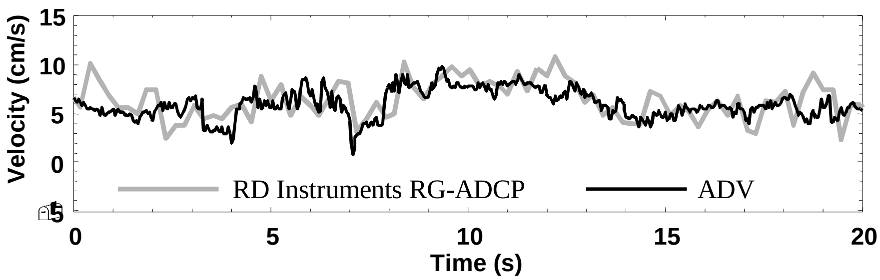


Figure 3. Radial velocities measured in a beam of the RG-ADCP with an ADV

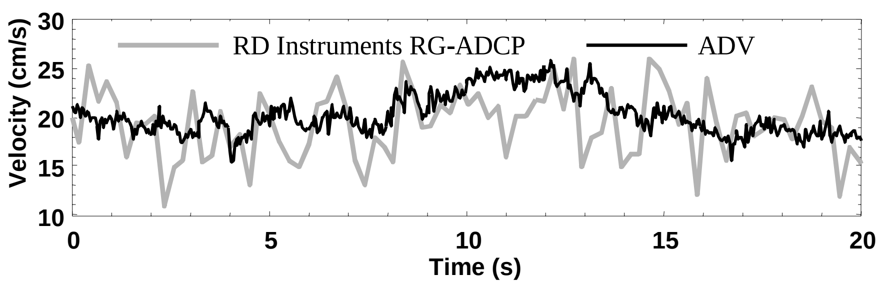
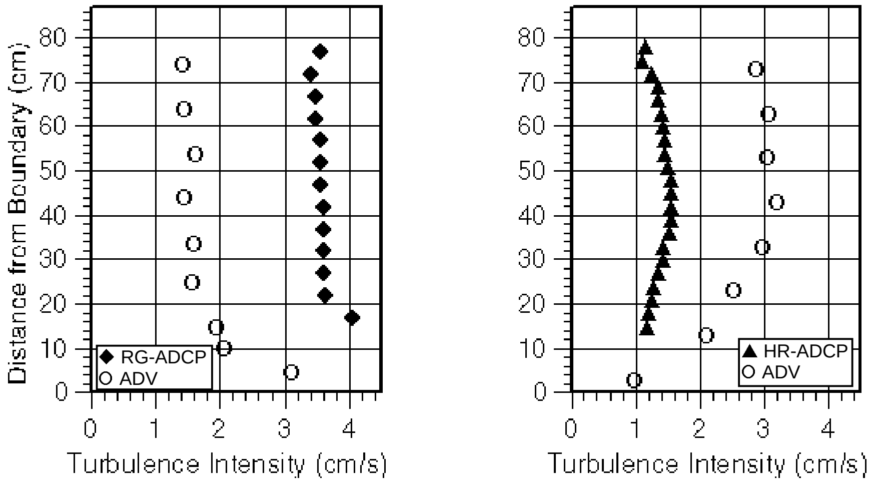


Figure 4. Streamwise velocities measured in a beam of the RG-ADCP with an ADV

Turbulence intensities were consistently overestimated in resolved single-ping data (Figure 5a) and produced errors as large as 125% away from boundaries. Doppler noise and resolution of multi-dimensional velocity from multiple-point velocities appear to dominate the errors. Internal averaging of pings in the HR-ADCP (about 20 pings were averaged for each recorded profile) decreased the effect of Doppler noise in streamwise turbulence intensities and typically resulted in an overall *under*estimation of vertical turbulence intensities (Figure 5b) by about 75%.

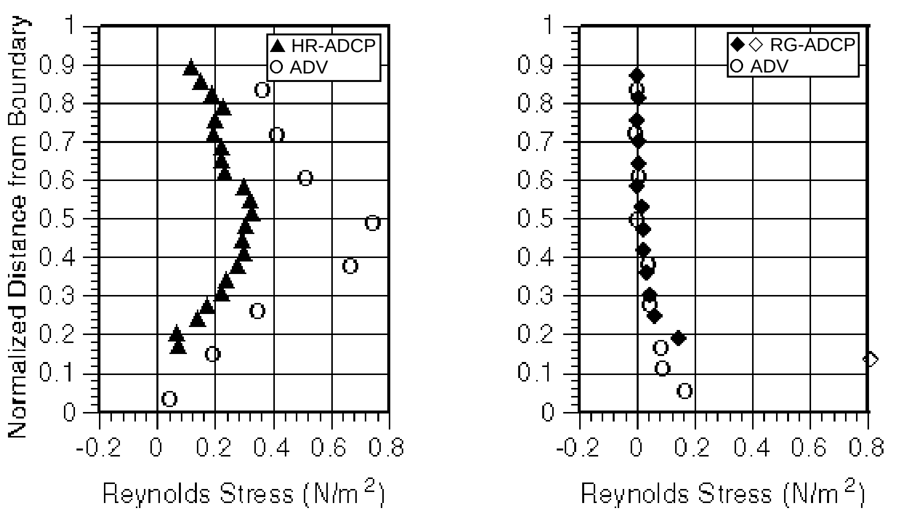


(a) RG-ADCP and ADV
streamwise turbulence intensity

(b) HR-ADCP and ADV
vertical turbulence intensity

Figure 5. ADCP and ADV turbulence intensity profiles

The HR-ADCP, a three-beam ADCP, consistently underestimated streamwise-vertical Reynolds stresses by approximately 50% (Figure 6a), whereas the RG-ADCP, a four-beam Janus configuration ADCP, measured Reynolds stresses with much better absolute accuracy (Figure 6b). Lohrmann and others (1990) showed that the horizontal-vertical Reynolds stress components aligned with the beam pairs of a Janus-configured instrument are unaffected by instantaneous inhomogeneity. Furthermore, Stacey and others (1999) showed that if the Doppler noise is uncorrelated with the velocity fluctuations, these Reynolds stress components are unaffected by Doppler noise. Reynolds stresses measured with the RG-ADCP showed significant boundary effects--for example, the open-diamond outlier in Figure 6b. Although this may be primarily a laboratory effect, it could have important consequences in field measurements.



(a) HR-ADCP and ADV
streamwise-vertical Reynolds stress

(b) RG-ADCP and ADV
streamwise-vertical Reynolds stress

Figure 6 ADCP and ADV streamwise-vertical Reynolds stress profiles

Potential Solutions

Manufacturers are constantly working to improve the accuracy of their instruments. Instruments and modes that have been introduced since the measurements reported herein were made (2001) provide faster ping rates, smaller bin sizes, and improved processing algorithms. Nevertheless, both of the considerations discussed below will need to be addressed to fully increase the effectiveness of ADCP turbulence measurements.

Reduction of minimum measurement volume. This is perhaps most easily and effectively achieved through reduction of bin size. The benefit gained from smaller bins reaches a limit, however, when the bin size is smaller than the transducer diameter. At that point, the largest dimension of the measurement volume is no longer controlled by bin size, and other methods are needed to decrease measurement volume. Reduction of bin size may be of lesser importance than the accuracy of Doppler shift measurement because the velocity gradients over the minimum bin size of many instruments are comparable to or smaller than the instantaneous measurement errors.

Reducing bin size also increases the amount of data collected. Although this is advantageous from a scientific viewpoint, it will require increased rates of data processing, transfer and recording to avoid a reduction in the temporal resolution of a measurement. A substitution of spatial for temporal resolution could be made through a “burst-bin” profiling mode; similar to the burst pinging often used in long-term, self-contained deployments. In a burst-bin mode, an ADCP might make measurements with 1-mm bins that are separated by 0.5 m, thereby resolving the small scales of the flow without compromising measurement frequency.

Reduction of errors resulting from inhomogeneous flow between beams. This will involve more than just refinement of currently available systems because these errors are caused by an invalidation of one of the basic assumptions that make three-dimensional velocity measurements possible with monostatic ADCPs. One possible solution is the use of bistatic profilers in a form similar to that of the ADV as illustrated in Figure 1a. Profilers of this form would use a single measurement volume for each bin, thereby eliminating the homogeneity assumption, decreasing the number of sampling volumes by a factor equal to the number of beams, and essentially eliminating side-lobe interference and the effects of transducer ringing. This form of profiler could also allow direct measurement of vertical velocity over part of the profile by using the central transducer as both a receiver and a transmitter. The potential dramatic reduction in beam angles could decrease the accuracy of horizontal velocity measurements, however.

Obtaining the most accurate turbulence measurements with the currently available commercial profilers will require that the sources of error discussed herein be minimized. The following practices will help minimize the effects of these sources of error and thereby provide the most reliable data from commercially available profilers.

1. Use an instrument with a high ping rate (5 Hz or better if possible) and record single ping data.
2. If appropriate, use the smallest bin size available for the mode and instrument.
3. Use the lowest noise mode available that is suitable for the site.
4. Be aware of the limitations imposed by each processing mode and by the flow conditions. For example, do not expect accurate results in highly inhomogeneous flow, such as near underwater structures such as weirs.
5. Use small beam angles to minimize beam spread; however, this can decrease the accuracy of horizontal velocity measurements.

6. Use a vertical beam to make direct measurements of vertical velocity.
7. Use a Janus orientation instrument aligned with the direction of interest. This allows isolation of horizontal components from only two beams and computation of Reynolds stresses unbiased by resolution from multiple points and Doppler noise. For unbiased measurements, noise must be uncorrelated with velocity.

Conclusions

The accuracy of turbulence measurements made with commercially available ADCPs is often poor in comparison to conventional measurement techniques, but ADCPs can provide reasonable estimates of many turbulence parameters. The ADCPs that are currently commercially available have several limitations in their ability to measure turbulence. These limitations result from the inaccuracy of velocity measurements and the poor temporal and spatial resolution of the instruments. Velocity measurement accuracy is limited by errors in Doppler shift measurement and by inhomogeneous flow between beams. Temporal resolution is limited by the pinging frequency of the instrument and spatial resolution is limited by minimum bin sizes and beam widths. Some turbulence statistics can be more accurately determined using certain beam orientations, such as the horizontal-vertical Reynolds stress components measured with Janus-orientation instruments.

Recent technology has resulted in improved Doppler shift measurement and temporal and spatial resolution; however, the use of multiple diverging beams to resolve multidimensional velocities does not provide fully reliable results and will require modification of ADCP configuration. Although the sources of error and limitations involved in measuring turbulence with ADCPs currently cannot be completely avoided, their effects can be minimized through the use of certain measurement configurations, beam orientations, and processing modes.

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